Distributed Systems

10. Quorum-Based Consensus: Paxos

Paul Krzyzanowski

Rutgers University

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Consensus Goal

Allow a group of processes to agree on a result

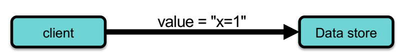
- All processes must agree on the same value
- The value must be one that was submitted by at least one process (the consensus algorithm cannot just make up a value)

We saw versions of this

- Mutual exclusion
  - Agree on who gets a resource or who becomes a coordinator
- Election algorithms
  - Agree on who is in charge
- Other uses of consensus:
  - Synchronize state to manage replicas: make sure every group member agrees on the message ordering of events
  - Manage group membership
  - Agree on distributed transaction commit
- General consensus problem:
  - *How do we get unanimous agreement on a given value?*

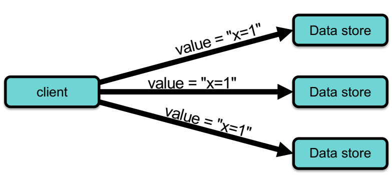
value = sequence number of a message, key=value, operation, whatever…

Achieving consensus seems easy!



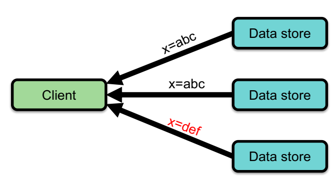
- One request at a time
- Server that never dies

Servers might die – let's add replicas



- One request at a time

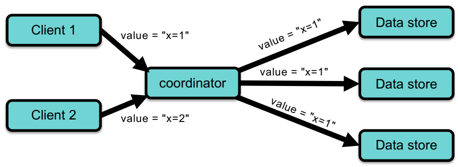
Reading from replicas is easy



We rely on a quorum (majority) to read successfully

No quorum = failed read!

What about concurrent updates?



- Coordinator processes requests one at a time
- But now we have a single point of failure!
- We need something safer

Consensus algorithm goal

Goal: agree on one result among a group of participants

Create a fault-tolerant consensus algorithm that does not block if a majority of processes are working

- Processors may fail (some may need stable storage)
- Messages may be lost, out of order, or duplicated
- If delivered, messages are not corrupted

Quorum: majority (>50%) agreement is the key part: If a majority of coins show heads, there is no way that a majority will show tails at the same time.

If members die and others come up, **there will be one member in common** with the old group that still holds the information.

Consensus requirements

- Validity
  - Only proposed values may be selected
- Uniform agreement
  - No two nodes may select different values
- Integrity
  - A node can select only a single value
- Termination (Progress)
  - Every node will eventually decide on a value

Paxos (Παξος)
Consensus algorithm

Paxos

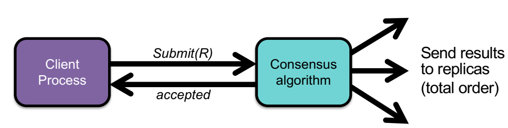
Goal: agree on a single value even if multiple systems propose different values concurrently

Common use: provide a consistent ordering of events from multiple clients
- All machines running the algorithm **agree on a proposed value** from a client
- The *value* will be associated with an event or action
- Paxos ensures that no other machine associates the value with another event

Fault-tolerant distributed consensus algorithm
- Does not block if a majority of processes are working
- The algorithm needs a majority (*2P+1*) of processors survive the simultaneous failure of *P* processors

Paxos provides **abortable consensus**
- A client's request may be rejected
- It then has to re-issue the request

A Programmer's View



If your request is not accepted, you can submit it again later:

```
while (submit_request(R) != ACCEPTED) ;
```

Think of R as a key:value pair in a database where multiple clients might want to modify the same key

Paxos players

- **Client**: makes a request
- **Proposers**:
  - Get a request from a client and run the protocol to get everyone in the cluster to agree
  - Leader: elected coordinator among the proposers (not necessary but simplifies message numbering and ensures no contention) – we don't need to rely on the presence of a single leader
- **Acceptors**:
  - Multiple processes that remember the state of the protocol
  - Quorum = any majority of acceptors
- **Learners**:
  - When agreement has been reached by acceptors, a Learner executes the request and/or sends a response back to the client

These different roles are usually part of the same system

Proposal numbers

- **Paxos ensures a consistent ordering in a cluster of machines**
  - Events are ordered by sequential event IDs (*N*)
- Client wants to log an event: sends request to a Proposer
  - E.g., *value, v* = "*add $100 to my checking account*"
- **Proposer**
  - Increments the latest proposal number (event ID) it knows about
    - ID = sequence number
  - Asks all the acceptors to reserve that proposal #
- **Acceptors**
  - A majority of acceptors have to accept the requested proposal #

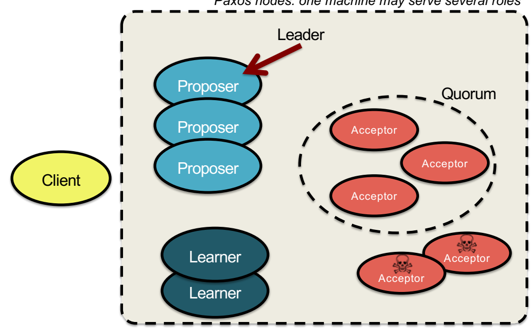
Proposal Numbers

- Each proposal has a unique number (created by proposer)
  - Must be unique (e.g., <sequence #>.<process_id>)
- Newer proposals take precedence over older ones
- Each acceptor
  - Keeps track of the largest number it has seen so far
  - Lower proposal numbers get rejected
    - Acceptor sends back the *{number, value}* of the currently accepted proposal
    - Proposer has to "play fair":
      - It will ask the acceptors to accept the *{number, value}*
      - Either its own or the one it got from the acceptor

Paxos in action

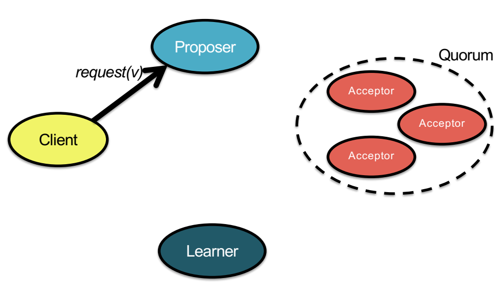
Goal: have all acceptors agree to a value *v* associated with a proposal

Paxos nodes: one machine may serve several roles



Paxos in action: Phase 0

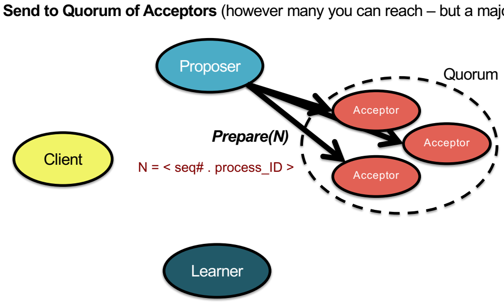
Client sends a request to a proposer



Paxos in action: Phase 1a – *PREPARE*

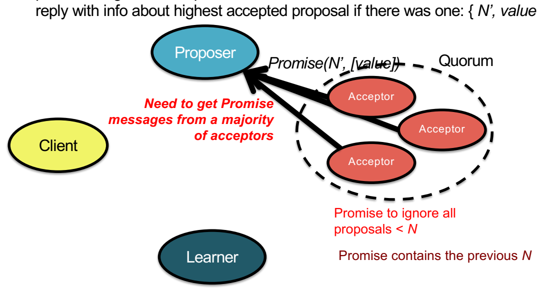
Proposer: creates a *proposal #N (N acts like a Lamport time stamp)*, where *N* is greater than any previous proposal number used by this proposer

Send to Quorum of Acceptors (however many you can reach – but a majority)



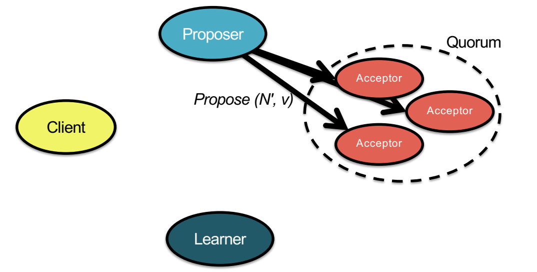
Paxos in action: Phase 1b – *PROMISE*

Acceptor:
if proposer's ID > any previous proposal
promise to ignore all requests with IDs < N
reply with info about highest accepted proposal if there was one: { *N', value* }



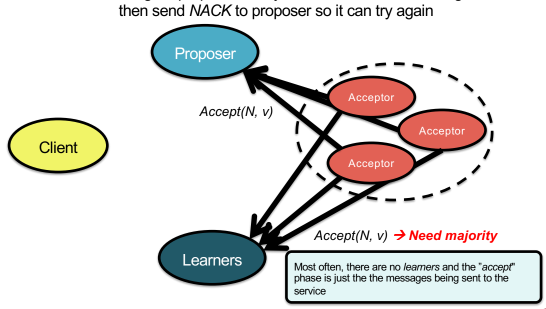
Paxos in action: Phase 2a – *PROPOSE*

Proposer: if proposer receives promises from the quorum (majority):
Attach a value *v* to the proposal (the event).
Send ***Propose*** to quorum with the **chosen** value
If promise was for another {*N', v*}, proposer MUST accept *v* for the **highest** accepted proposal



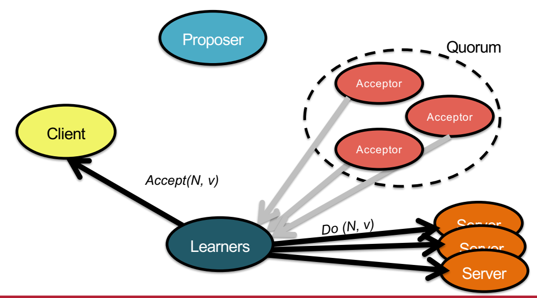
Paxos in action: Phase 2b – *ACCEPT*

Acceptor: if the promise still holds, then announce the value *v*
Send ***Accepted*** message to Proposer and every Learner
BUT: if a higher proposal # may have been received during this time
then send *NACK* to proposer so it can try again



Paxos in action: Phase 2c – *ACCEPT*

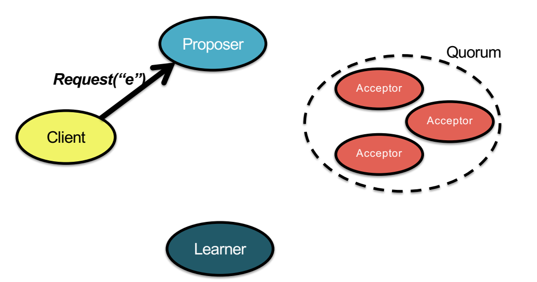
Learner: Respond to client and/or take action on the request



Paxos: A Simple Example – All Good

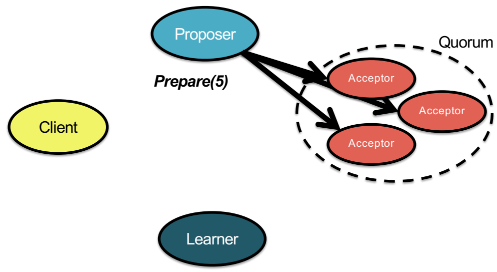
Paxos in action: Phase 0

Client sends a request to a proposer



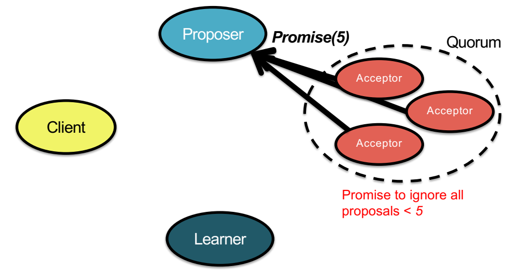
Paxos in action: Phase 1a – *PREPARE*

Proposer: picks a sequence number: 5
Send to Quorum of Acceptors



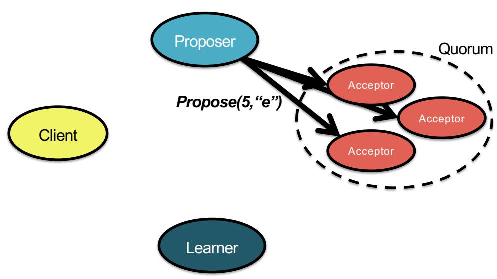
Paxos in action: Phase 1b – *PROMISE*

Acceptor: Suppose 5 is the highest sequence # any acceptor has seen
Each acceptor PROMISES not to accept any lower numbers



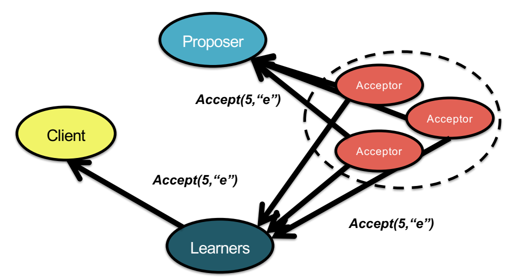
Paxos in action: Phase 2a – *ACCEPT*

Proposer: Proposer receives the promise from a majority of acceptors
Proposer must accept that <seq, value>



Paxos in action: Phase 2b – *ANNOUNCE*

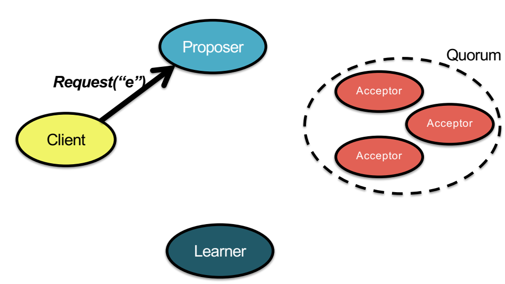
Acceptor: Acceptors state that they accepted the request



Paxos: A Simple Example – Higher Proposal

Paxos in action: Phase 0

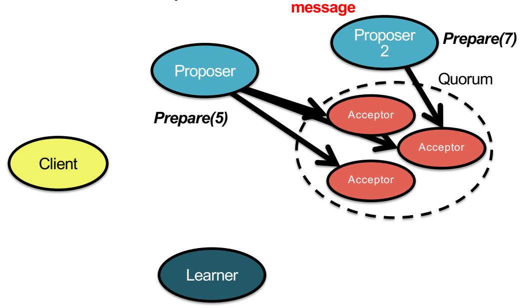
Client sends a request to a proposer



Paxos in action: Phase 1a – *PREPARE*

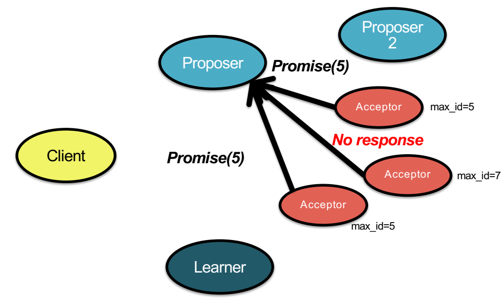
Proposer: picks a sequence number: 5
Send to Quorum of Acceptors

One acceptor receives a higher offer BEFORE it gets this PREPARE message



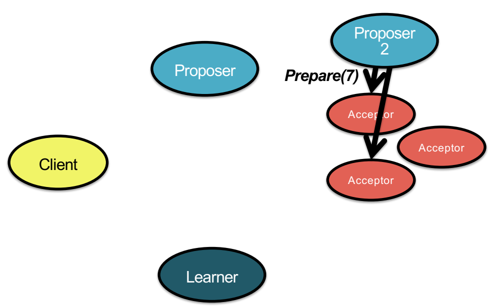
Paxos in action: Phase 1b – *PROMISE*

Acceptor: If an acceptor previously received a higher ID, it will not respond



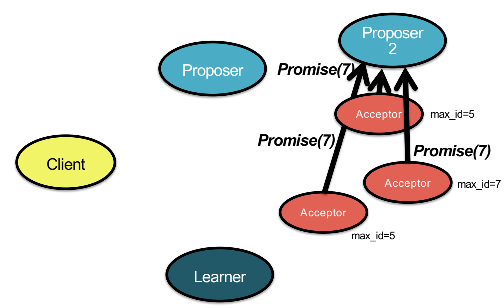
Paxos in action: Phase 1a – *PREPARE*

Proposer: The other proposer's messages now reach the other acceptors
Send to Quorum of Acceptors



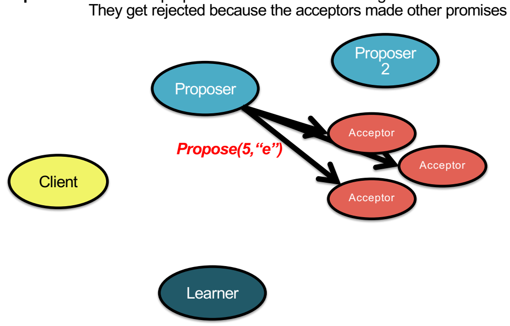
Paxos in action: Phase 1b – *PROMISE*

Acceptor: Higher proposal numbers will get promises fulfilled
Proposer 2 gets a quorum of responses



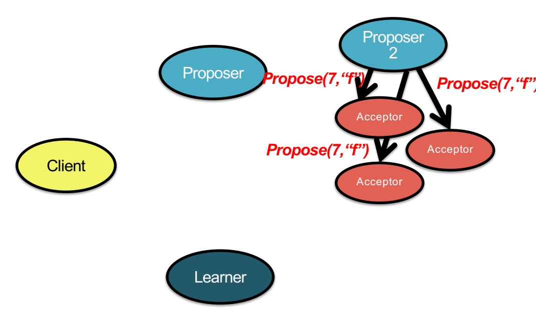
Paxos in action: Phase 2a – *ACCEPT*

Proposer: Now the first proposer sends ACCEPT messages
They get rejected because the acceptors made other promises



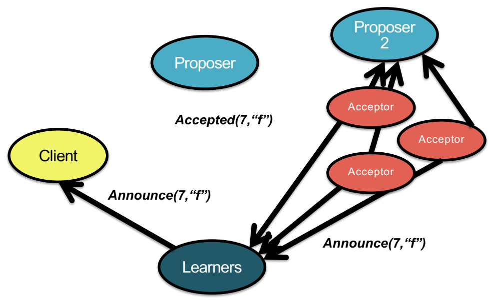
Paxos in action: Phase 2a – *ACCEPT*

Proposer: The second proposer's messages are accepted – it's the highest ID



Paxos in action: Phase 2b – *ANNOUNCE*

Acceptor: Acceptors state that they accepted the request



Paxos: Keep trying if you need to

- A proposal *N* may fail because
  - The acceptor may have made a new promise to ignore all proposals less than some value *M* >*N*
  - A proposer does not receive a quorum of responses: either *promise* (phase 1b) or *accept* (phase 2b)
- Algorithm then has to be restarted with a higher proposal #

Paxos summary

- Paxos allows us to ensure consistent (total) ordering over a set of events in a group of machines
  - Events = commands, actions, state updates
- Each machine will have the latest state or a previous version of the state
- Paxos used in:
  - Google Chubby lock manager / name server
  - Apache Zookeeper (clone of Google Chubby)
  - Cassandra lightweight transactions
  - Google Spanner, Megastore
  - Microsoft Autopilot cluster management service from Bing
  - VMware NSX Controller
  - Amazon Web Services, DynamoDB

Paxos summary

To make a change to the system:

- Tell the *proposer* (leader) the event/command you want to add
  - Note: these requests may occur concurrently
  - Leader = one elected proposer. Not necessary for Paxos algorithm but an optimization to ensure a single, increasing stream of proposal numbers. Cuts down on rejections and retries.
- The proposer picks its next highest event ID and asks all the acceptors to reserve that event ID
  - If any acceptor sees has seen a higher event ID, it rejects the proposal & returns that higher event ID
  - The proposer will have to try again with another event ID
- When the **majority of acceptors accept the proposal**, accepted events are sent to learners, which can act on them (e.g., update system state)
  - Fault tolerant: need *2k+1* servers for *k* fault tolerance

Implementation

- Use only one proposer at a time – the leader
  - Other nodes can be active backups just in case the leader dies
  - No need to worry about sync of proposal # – those are local per proposer
  - Acts like a fault-tolerant coordinator
    - Avoids failed proposals due to higher numbers from other proposers
- Alternatively, embed proposer logic into client library
  - Too many clients issuing concurrent requests can cause a large # of retries
- Learners rarely needed
  - Acceptors are often running on the system that processes the request (e.g., data store, log, …)
  - Just send an acknowledgement directly to the client.

The End